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Testing a turbo-jet combustion chamber to check analytical design

Nester, Robert Gardiner

St. Paul, Minnesota; University of Minnesota

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TESTING A TURBO-JET COMBUSTION CHAMBER
TO CHECK
ANALYTICAL DESIGN

A Thesis
Submitted to the Graduate Faculty
of the
University of Minnesota

by
Robert G. ^{Anderson} Nester

In Partial Fulfillment of the Requirements for
The Degree of
Master of Science in Aeronautical Engineering

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ACKNOWLEDGEMENTS

The author would like to express his appreciation to the following people who aided in this investigation: Professor B. J. Robertson and Thomas E. Murphy for their assistance, technical advice, and counseling.

Messrs. K. E. Neumeler, W. Alden, L. Clauten and C. O. Lund for their assistance in manufacturing and setting up the test equipment.

MEMORANDUM

The subject of this memorandum is the proposed
to the following people who are in the investigation
Professor J. A. Johnson and James E. Smith for their
analysis, financial advice, and planning.
James E. Smith, a student, is also a student and
J. A. Smith for their analysis in planning and
meeting up the last year.

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SUMMARY

The results obtained in this investigation to establish the validity of certain pressure drop parameters used in the design of a turbo-jet combustion chamber indicate the performance of the combustor can be predicted by analytical methods.

All computed values of both the friction pressure drop and the pressure drop due to momentum changes with heat addition were lower, in that region of air flows wherein the combustor would normally operate, than those indicated by analysis of the experimental data. The maximum observed error of eight percent occurred for the condition of 2.5 pounds per second air flow. The average percentage error over the entire operating range investigated was approximately 2 percent. The combustor inlet air conditions, under which these runs were made was equivalent to a simulated altitude of 27,000 feet at the design point investigated.

The reproducibility of experimental data was difficult. Allowance must be made for obstructions or irregularities of the flow passages as warping of the combustor basket, or carbon depositions. In the final analysis, for accurately computing the total pressure drop across the combustor, the effect of mixing the relatively cold secondary air with the products of combustion must be taken into account.

The present method is being investigated by

establishing the value of various factors and determining
 the effect of a factor of constant value on the
 rate of the reaction of the mixture and is limited by
 physical factors.

All physical factors of both the reaction mixture

and the reaction itself are determined by the
 addition of water, in that order of air flow through the
 system which would normally operate. The flow indicated by
 the rate of the reaction itself. The system operated
 over a range of about 1000 to 2000 for the reaction of 1.5
 grams per cubic air flow. The system operated when
 over the entire operating range. The system was operated
 at 1000. The system had air flow, which
 was then used as a standard in a standard
 of 1000. The system had air flow, which

The relationship of experimental data was

different. The system had air flow, which was
 determined at the time of the reaction of the mixture
 and, in some cases, in the final analysis, for
 comparison with the data obtained from the
 reaction of the mixture of the mixture with water.
 The effect of the reaction of the mixture with water
 was also determined by the reaction of the mixture with water.

INTRODUCTION

All turbo-jet engines add energy to air taken in from the surrounding atmosphere and exhaust the products at a higher velocity thus producing thrust. At present the most common method of adding the energy necessary is through the combustion of hydrocarbon fuels with air in the combustion chamber.

The flow of gas through a combustion chamber is accompanied by losses that effect the overall efficiency of the turbo-jet engine to a marked degree. The losses in the combustion chamber may be classified as the total friction pressure loss due to configuration and friction and the pressure loss due to the momentum change with heat addition. Friction pressure losses result from the turbulent flow of the gases over the metal surfaces of the ducting and through the orifices leading into the combustion zone. These losses can be measured during non-firing runs with the combustion chamber, and their values used in computing the pressure loss due to momentum changes during firing runs. This is an approximation but the percentage error is very small. Actually there is a change in the density of the entering air due to a change in temperature that is not indicated in a non-firing run.

EXHIBIT

All things for which the law is made in
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Friction pressure losses are usually responsible for two-thirds of the total pressure loss, and is highest in contra-flow combustion chambers and lowest in straight flow chambers with low entrance velocities.

The momentum pressure losses occur as a result of the combustion process in changing the velocity and density of the gases. An exact solution for the momentum pressure loss in a duct of constant cross-sectional area is presented in the appendix. Normally an exact solution is not required when the Mach numbers in the combustion zone are on the order of 0.2 or less than 0.3. The exact solution presented is modified to the extent that the addition of fuel and area change has been neglected. Therefore, the calculated momentum pressure loss will be lower than that derived by experiment.

The importance of minimizing the total pressure loss in the combustor is comparable with keeping the efficiencies of the compressor and turbine as high as possible. Combustion chambers must be designed for the lowest possible pressure drop due to friction and this is possible by eliminating abrupt changes in section, reverse turns in the ducting, minimum initial velocity in the flow passages and maximum area flow passages.

PURPOSE OF INVESTIGATION

It is the purpose of this investigation to establish the validity of certain analytical pressure loss design parameters used in the design of a turbo-jet combustion chamber of similar configuration. The check will be made by comparison with experimental data. In the case of the friction pressure drop, a second comparison will be made using the method set forth in the National Advisory Committee for Aeronautics, Technical Note, Number 1180.

As more and more information of this sort is accumulated the design of combustion chambers for turbo-jet engines will become less of a cut and try process and the need for expensive experimental test setups will be lessened.

REMARKS ON INVESTIGATION

It is the purpose of this investigation to determine the value of the various methods of investigation in the design of a machine. The design of a machine is a process of trial and error. The designer starts with a rough sketch of the machine and then proceeds to refine it. The process is iterative, and the designer must be prepared to make changes as he goes along. The value of the various methods of investigation is determined by the extent to which they aid the designer in this process. The methods of investigation are: 1. The use of a model. 2. The use of a scale. 3. The use of a diagram. 4. The use of a photograph. 5. The use of a motion picture. 6. The use of a microscope. 7. The use of a spectrometer. 8. The use of a balance. 9. The use of a thermometer. 10. The use of a barometer. 11. The use of a hygrometer. 12. The use of a windmill. 13. The use of a water pump. 14. The use of a steam engine. 15. The use of a gas engine. 16. The use of a diesel engine. 17. The use of a turbine. 18. The use of a motor. 19. The use of a generator. 20. The use of a transformer. 21. The use of a switch. 22. The use of a relay. 23. The use of a contact. 24. The use of a plug. 25. The use of a pin. 26. The use of a screw. 27. The use of a nut. 28. The use of a bolt. 29. The use of a washer. 30. The use of a gasket. 31. The use of a seal. 32. The use of a bearing. 33. The use of a bush. 34. The use of a sleeve. 35. The use of a collar. 36. The use of a flange. 37. The use of a rim. 38. The use of a hub. 39. The use of a shaft. 40. The use of a pulley. 41. The use of a wheel. 42. The use of a gear. 43. The use of a rack. 44. The use of a pinion. 45. The use of a worm. 46. The use of a bevel. 47. The use of a spur. 48. The use of a helical. 49. The use of a double. 50. The use of a triple. 51. The use of a quadruple. 52. The use of a quintuple. 53. The use of a sextuple. 54. The use of a septuple. 55. The use of an octuple. 56. The use of a nonuple. 57. The use of a decuple. 58. The use of a undecuple. 59. The use of a duodecuple. 60. The use of a tredecuple. 61. The use of a quattuordecuple. 62. The use of a quindecuple. 63. The use of a sexdecuple. 64. The use of a septendecuple. 65. The use of an octodecuple. 66. The use of a nonadecuple. 67. The use of a vigintuple. 68. The use of a unguicuple. 69. The use of a duogicuple. 70. The use of a triogicuple. 71. The use of a tetragicuple. 72. The use of a pentagicuple. 73. The use of a hexagicuple. 74. The use of a heptagicuple. 75. The use of an octogicuple. 76. The use of a nonagicuple. 77. The use of a sexagesicuple. 78. The use of a septuagesicuple. 79. The use of an octogicesicuple. 80. The use of a nonagesicuple. 81. The use of a centogicesicuple. 82. The use of a centogicuple. 83. The use of a centogicesicuple. 84. The use of a centogicesicuple. 85. The use of a centogicesicuple. 86. The use of a centogicesicuple. 87. The use of a centogicesicuple. 88. The use of a centogicesicuple. 89. The use of a centogicesicuple. 90. The use of a centogicesicuple. 91. The use of a centogicesicuple. 92. The use of a centogicesicuple. 93. The use of a centogicesicuple. 94. The use of a centogicesicuple. 95. The use of a centogicesicuple. 96. The use of a centogicesicuple. 97. The use of a centogicesicuple. 98. The use of a centogicesicuple. 99. The use of a centogicesicuple. 100. The use of a centogicesicuple.

APPARATUS AND INSTRUMENTATION

Combustor

The combustor used in these tests was one of fourteen used in the General Motors J-33 Turbo-Jet Engine. It was a special combustor, modified to the extent that the inner-combustor connecting flame tubes were not included in its construction. A sketch of the combustor is shown in Figure 2.

A special air adapter was made to fit the outer liner to eliminate certain variances in the entering air flow. The air adapter provides the mounting for the fuel nozzle, the igniter plug, and the inner liner dome and also supports the forward end of the outer combustion chamber. The inner liner is supported at the entrance end by the dome, and is positioned at the exit ends by a liner-locating dowel. The grooves at the forward end of the outer combustion chamber retain two piston rings. These rings enter into the counter-bore of the adapter, forming an air seal between the adapter and the outer combustion chamber, and provides for any expansion or contraction.

Air enters the outer and inner combustion chambers through the adapter. Primary air is introduced into the combustion zone through a series of holes surrounding the

The following is a list of the names of the persons who were present at the meeting of the Board of Directors of the United States National Bank, held on the 10th day of January, 1900, at New York City.

[illegible]

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fuel nozzle in the center of the flame tube dome and through holes in the upstream section of the inner combustion chamber. The air entering the holes around the fuel nozzle is deflected by spiral plates inside the dome. This allows maximum mixing of the fuel with the incoming air while establishing a low velocity ignition area with some control of the flame front.

Secondary air, necessary for completion of combustion and cooling, is introduced through a series of 5/8 inch holes and louvers located in the inner combustion chamber downstream from the primary air entry.

The fuel injection system for the combustor consists of an electrically driven fuel pump and one fuel nozzle of the hollow cone spray type. In the nozzle, fuel flows in through tangential slots in the spray tip and out through the tip orifices into the combustion chamber. At fuel pressures below 125 pounds per square inch the arc of the spray is approximately seventy degrees. At higher pressures the arc narrows and the flow is extended farther into the combustion chamber.

The fuel ignition system employed is that of a high intensity spark combined with an acetylene gas jet. The acetylene gas is fed into the cooling air space between the electrodes and the surrounding ceramic insulation. This insures a positive initial burning and eliminates explosive hot starts. The spark plug used was a General Electric Model 7 HS 40A2.

Test Setup

The general arrangement of the test setup is diagrammatically shown in Figure 1. Air was supplied by the auxiliary compressor section of a 1710 Allison Vee 12 engine. (Figure 5) Desired combustor inlet air conditions were obtained by regulation of the Allison engine speed and the combustor exhaust waste gate. The air mass flow was measured by a thin plate orifice located upstream of the compressor.

The inlet duct was fabricated of mild steel to fit the dimensions of the existing air supply ducting and the combustor. The exhaust duct was fabricated of 20 gauge stainless steel and designed to fit the exit of the combustor and to exhaust into the atmosphere. Figure 1 shows the longitudinal cross-section of the inlet duct, the combustor, and the exhaust duct with the location of the instrument stations. Figure 4 shows arrangement of the test setup as installed in the test cell.

Instrumentation

Positions and arrangements of the thermocouples and pressure taps as located in the inlet and exhaust ducts and the combustor are shown diagrammatically in Figure 3.

The velocity profile and the mean velocity of the air flow entering the combustor were determined by three

The Council recommended that the Commission should be authorized to make a study of the situation in the various countries of the world, with a view to determining the extent of the problem and the measures which should be taken to deal with it.

[illegible][illegible]

total head tubes and one static pressure tap located upstream at station 1. This section has a cross-sectional area of .1965 square feet. The temperature of the entering air was measured with an iron-constantan thermocouple.

Determination of the pressure level and the mass flow change of the secondary air along the longitudinal axis of the combustor between the inner and outer liners was attempted through a series of static pressure taps and total head tubes at stations 2, 3, and 4. Station 2 is located just downstream of the primary air inlets at the beginning of the secondary air ports. Stations 3 and 4 are located at the mid-point and at the end of the secondary air ports, respectively. For measuring velocity distribution at the exit of the flame tube during non-firing runs, three pitot-static tubes were inserted into the stream at station 5. For measurement of velocity and total pressure during hot runs, a shielded total head tube and a static pressure tap were used.

Chromel-Alumel thermocouples were used throughout for total temperature measurement of the hot gases, and indications were taken as true with no corrections for radiation or stagnation effects. The temperature distribution of the exhaust gases was measured by a total temperature rake consisting of four thermocouples as shown in Figure 3. The mean combustor exhaust temperature was taken as the arithmetic mean of the temperatures measured

1. The first section of the report is a general statement of the purpose and scope of the study. It states that the purpose of the study is to determine the effect of the new tax law on the income of individuals. The scope of the study is limited to the income of individuals who are subject to the new tax law.

2. The second section of the report is a description of the sample used in the study. It states that the sample consists of 100 individuals who are subject to the new tax law. The sample was selected from a list of individuals who were provided to the Internal Revenue Service.

3. The third section of the report is a description of the data collection process. It states that the data were collected from the individuals in the sample by sending them a questionnaire. The questionnaire asked for information about their income, their expenses, and their tax payments.

4. The fourth section of the report is a description of the data analysis process. It states that the data were analyzed using statistical methods. The methods used were the t-test and the chi-square test.

5. The fifth section of the report is a summary of the results of the study. It states that the results of the study show that the new tax law has a significant effect on the income of individuals. The effect is a decrease in income.

6. The sixth section of the report is a conclusion. It states that the results of the study support the hypothesis that the new tax law has a significant effect on the income of individuals. The effect is a decrease in income.

7. The seventh section of the report is a list of references. It lists the sources of information used in the study.

8. The eighth section of the report is an appendix. It contains the questionnaire used in the study.

by these four probes.

Mercury manometers were used throughout for total and static pressure measurements. For measuring dynamic pressure level, a bank of six inclined tube mercury manometers was used. Figure 6 shows the instrument recording panel.

Fuel flows were measured with a Fischer and Porter Company Flowrater with Stabil-Vis Viscosity Immune Float.

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PROCEDURE

Tests were made to evaluate the performance of the combustion chamber at various pressures and air flows. With the equipment available, the range was limited to a maximum of 46 inches of mercury absolute static pressure at the entrance to the combustion chamber and to three pounds per second air flow.

In order to evaluate the air flow and velocity distribution axially through the combustion chamber, a series of non-firing runs was made at varying combustor inlet static pressures. The data recorded were the total, dynamic, and static pressure level at the entrance; static pressure level of the air stream in the annular space surrounding the inner combustion chamber at the beginning, mid-point, and the end of the secondary air entrances to the combustion zone; and the total and static pressure levels at the exit of the combustor; and the friction pressure drop across the combustor.

To determine the total pressure drop, hot runs were made at set static pressure levels at the combustor entrance with varying mass flows. These runs were made at constant exit temperatures. Total entrance pressure, total and static exit pressures, total entrance temperature, mass

[illegible]

It is noted in the report that the air flow and velocity characteristics during the test were not uniform, and that the air flow was not uniform in the test section. The data presented in the report are based on the assumption that the air flow was uniform in the test section. The data presented in the report are based on the assumption that the air flow was uniform in the test section.

[illegible]

Flow and total pressure drop were recorded.

For determining the effect of entrance static pressure on mean temperature rise through the combustor, runs were made at several constant entrance pressures with varying fuel-air ratios. Those data recorded were: entrance temperature, exit temperature, air flow, fuel flow, and total pressure drop.

that the total number of cases was 100,000.

The following are some of the results:

1. The number of cases was 100,000 in 1910.

2. The number of cases was 100,000 in 1911.

3. The number of cases was 100,000 in 1912.

4. The number of cases was 100,000 in 1913.

5. The number of cases was 100,000 in 1914.

6. The number of cases was 100,000 in 1915.

7. The number of cases was 100,000 in 1916.

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9. The number of cases was 100,000 in 1918.

10. The number of cases was 100,000 in 1919.

11. The number of cases was 100,000 in 1920.

12. The number of cases was 100,000 in 1921.

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14. The number of cases was 100,000 in 1923.

15. The number of cases was 100,000 in 1924.

16. The number of cases was 100,000 in 1925.

17. The number of cases was 100,000 in 1926.

18. The number of cases was 100,000 in 1927.

19. The number of cases was 100,000 in 1928.

20. The number of cases was 100,000 in 1929.

21. The number of cases was 100,000 in 1930.

22. The number of cases was 100,000 in 1931.

23. The number of cases was 100,000 in 1932.

RESULTS AND DISCUSSION

The data obtained in this investigation to evaluate the performance of the combustor are summarized in Tables 1-5. Those runs wherein blowout or unstable combustion occurred are omitted because they have no bearing in this evaluation. The mean combustor outlet temperature indicated in Table 1 is the arithmetical mean of four readings taken at Station 5. Measured temperatures were very erratic. A representative distribution of combustor exit temperatures may be seen in Figure 8.

The combustor operated at efficiencies above 80 percent and was capable of producing outlet temperatures in excess of that deemed safe for operation at high back pressures. Figure 9 shows the effect of varying the combustor inlet pressure on the efficiency of the combustor. Curves of 100, 50, and 50 percent theoretical temperature rise are included for combustion efficiency estimation. When the entrance pressure was high the combustor operated at efficiencies above 90 percent except at fuel-air ratios of less than 0.01. This is due, in part, to poor atomization of the fuel used in the nozzle at low fuel pressures. The maximum efficiency occurred at an overall fuel-air ratio much leaner than the overall stoichiometric mixture.

As the inlet pressure was increased this maximum remained fairly constant at a fuel-air ratio of 0.014.

The effect of varying the inlet static pressure on total pressure drop is shown graphically in Figure 10. It is seen, that for any one selected air flow, the pressure drop decreased as the inlet pressure was increased. The pressure drop is a function of the inlet velocity which in turn is a function of the density of the gas stream. As the inlet pressure was increased the density of the entering air mass was increased and the velocity necessary to pass the mass flow was decreased. The control of the inlet pressure was made by regulation of the Allison compressor speed and by applying the necessary back pressure by reducing the effective area of the exhaust. Three runs were made at varying inlet pressure to give an indication of the manner in which the pressure drop varied. All runs were made at a mean combustor exit temperature of 1600 degrees Rankine.

Figures 11, 12, and 13 show the comparison of experimental and computed combustion chamber pressure losses. The calculated friction pressure loss by method I and indicated in Figure 11, is that presented by the National Advisory Committee for Aeronautics, Technical Note Number 1100. This method is based on the assumption that the pressure loss characteristics of the actual combustion chamber can be matched by those of an equivalent combustion chamber of constant cross-sectional area. It is also

As the child grows and matures his world expands

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assumed that the friction pressure loss takes place before the combustion process. This method was included in this investigation for a comparison check only. The calculated friction pressure drop, indicated Method II in Figure 12, is that presented by J. B. Verdin in a paper on the design of a turbo-jet combustion chamber, and is included in the Appendix.

Figure 13 is a comparison of the experimental momentum pressure drop with that computed. This method of computing the pressure drop due to momentum changes is included in the Appendix. The difference indicated in the curves is largely due to the neglect of the slight area change in the combustor (less than 3 percent) and the effect of the change in momentum involved in the mixing of the hot and cold gas streams.

The altitude condition simulated in this investigation was 27,000 feet density altitude. This simulated altitude prevailed at the design condition of 2.5 pounds per second air flow. The simulated altitude at the combustor entrance was computed from assumed data for a turbo-jet engine having a compressor compression ratio of four and a compressor efficiency of 90 percent.

It was found that the accurate reproduction of data was difficult at low compressor speeds. The Allison engine compressor used in supplying the air has an engine-compressor speed ratio of 3.5 to 1. A surge of 100 rpm engine speed,

of a person-for membership purposes, and he indicates in the
in case presented by J. E. WARD in a paper on the subject
of religious freedom, published in 1912 in volume 13,
number 1, pages 1-2. The subject is the subject of the
for membership purposes. This subject was included in 1912
and 1913. The subject is the subject of the subject of the subject

Plaza 11 is a combination of two apartments
situated on the top floor with two bedrooms. This apartment
occupies the entire top floor of the building and is
divided in two sections. The entrance is located in the
center of the building and is the subject of the slight
change in the building (see page 3) and the effect
of the change in structure involved in the design of the
new and old sections.

The above conditions mentioned in this investigation

It has found that the average population of the
is difficult to determine. The white
population was in 1911, and the
population of 1921 is a matter of 100,000.

therefore, would give an increase or decrease of 350 rpm of the compressor. In an attempt to smooth out the flow of air and approach the steady flow conditions necessary, one bank of the Allison engine was made inoperable. This improved conditions at low mass flows. It is suggested that in future investigations of this type a system of bleed-off be installed to eliminate this condition. At high compressor speeds no serious difficulty was encountered in reproducing data.

in technical detail.

TABLE NUMBER 1

EXPERIMENTAL								THEORETICAL		
W_a "Hg	W_f #/Hr	W_a #/sec	W_f #/sec	F/A	T_i °F	T_s °F	ΔT	100% ΔT	80% ΔT	60% ΔT
.65	53	1.705	0.0147	0.0086	140	525	385	646	518.5	389
.65	62	1.705	0.0172	0.0101	140	652	512			
.65	71	1.705	0.0197	0.0158	140	780	680	862	689	517
.65	79	1.705	0.0129	0.01285	140	915	775			
.65	88	1.705	0.0244	0.0143	140	1040	900			
.65	100	1.705	0.0278	0.0163	140	1175	1035	1210	977	726
.60	110	1.640	0.0306	0.01875	140	1310	1170			
.55	120	1.570	0.0334	0.02125	140	1460	1310	1560	1250	937

ENERGENE DIESEL FUEL # 2

HHV 19600 BTU/LB

SPGR 0.855

 $P_a = 29.12$ "Hg, $T_a = 90^\circ F$ $P_f = 34.2$ "Hg Abs.

TABLE NUMBER 3

ENTRANCE PRESSURE 43.2 "Hg ABS.							
ω_a "Hg	ω_f #/HR	ω_a #/SEC	ω_f #/SEC	F/A	T_1 °F	T_5 °F	
1.55	72	2.63	0.0200	0.0076	180	451	471
1.4	83	2.50	0.02308	0.00921	180	780	600
1.3	92	2.41	0.0256	0.0106	180	915	735
1.2	100	2.31	0.0278	0.0120	180	1040	860
1.07	110	2.182	0.0305	0.0140	180	1175	995
0.92	119	2.05	0.033	0.0161	180	1310	1130
0.86	128	1.96	0.0355	0.0181	180	1450	1270

$$P_a = 29.20 \text{ "Hg} \quad T_a = 90^\circ \text{F}$$

TABLE NUMBER 4

P_1 "Hg Abs	T_1 °F	ω_a "Hg	ω_u #/SEC	ΔP_F "Hg MEASURED	$\Delta P/P_1$ MEASURED	ΔP_F #/sq CALCULATED METHOD I	$\Delta P_F/P_1$ METHOD I	ΔP_F METHOD II	$\Delta P_F/P_1$ METHOD II
31.8	120	.35	1.26	0.6	0.0189	49.1	0.022	.75	.0236
33.7	140	.51	1.51	1.1	0.0326	70.6	0.0296	1.1	.0326
35.4	160	.70	1.77	1.4	0.0396	96.5	0.0381	1.49	.0420
39.3	180	1.15	2.281	2.1	0.0534	148	0.0533	2.32	.0590
42.4	205	1.4	2.50	2.8	0.066	171	0.0570	2.69	.0635
45.2	240	1.7	2.75	3.5	0.0774	203.6	0.0636	3.22	.0710

$$P_a = 29.1 \text{ "Hg Abs} \quad T_a = 95^\circ \text{F}$$

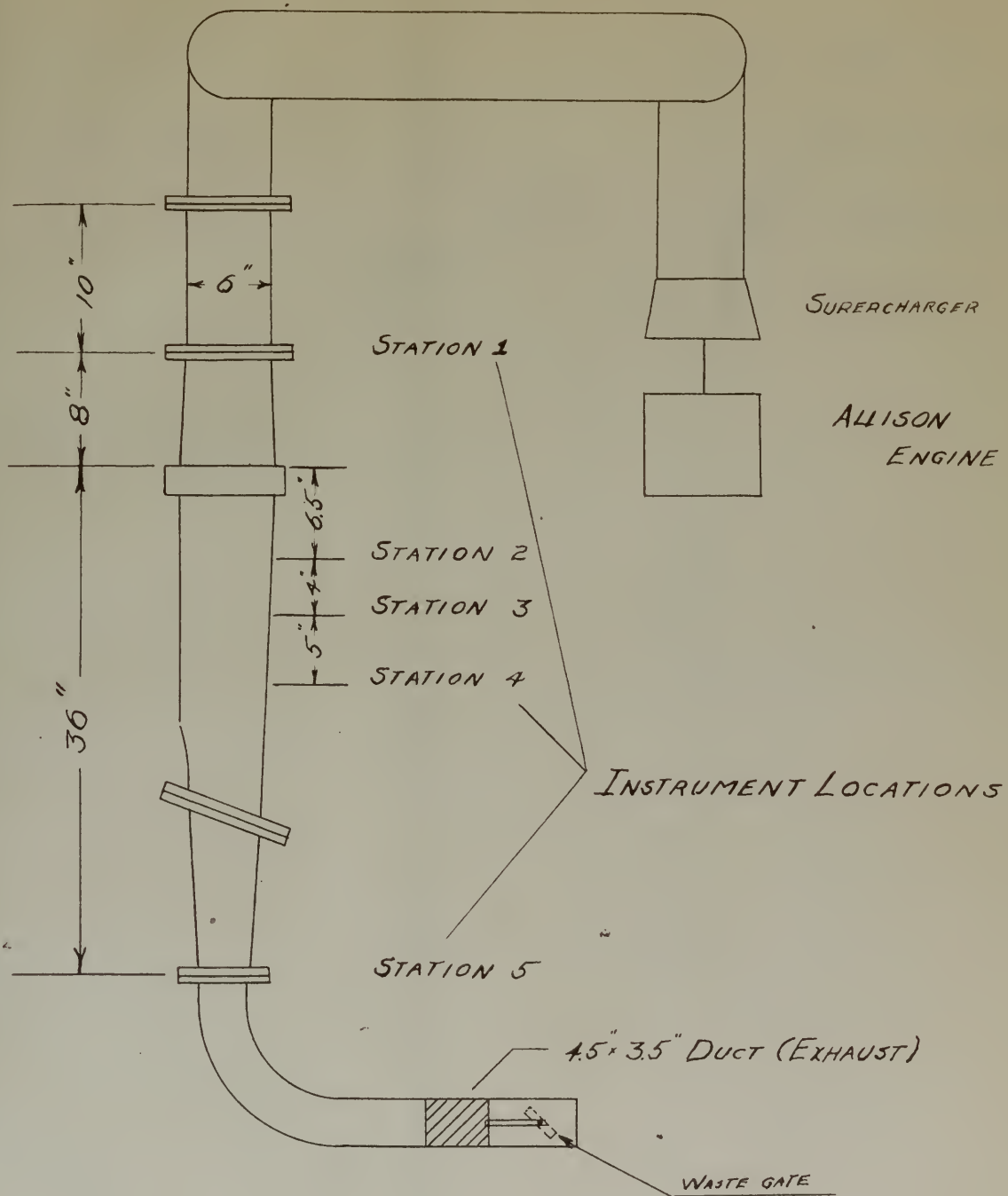


FIGURE 1

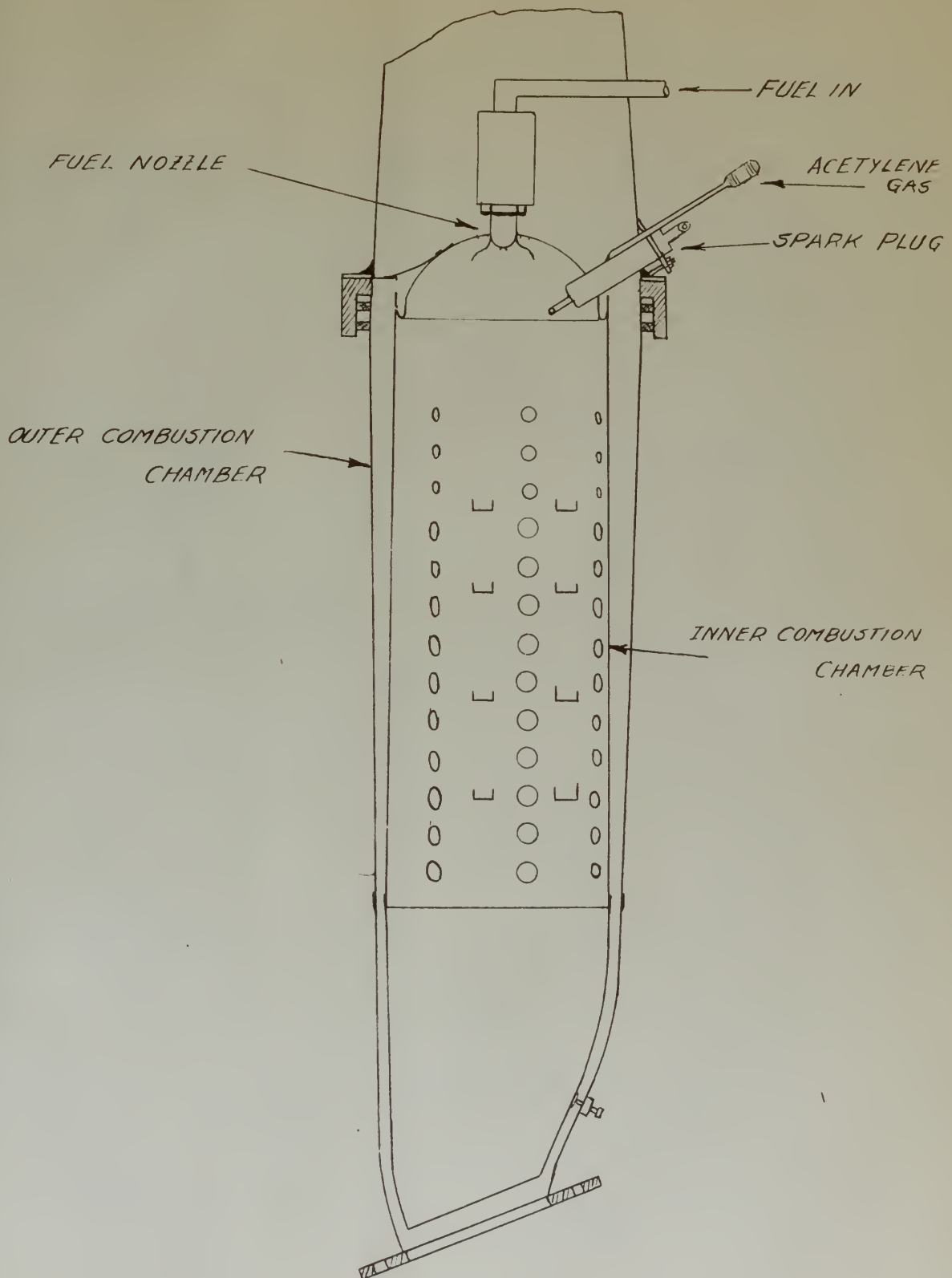
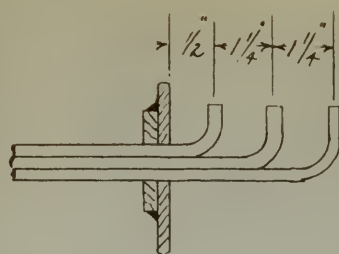
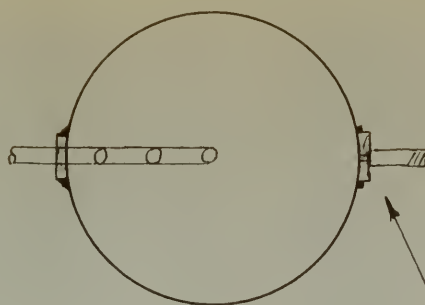


FIGURE 2

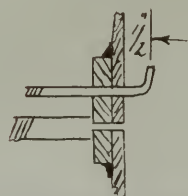


TOTAL HEAD RAKE

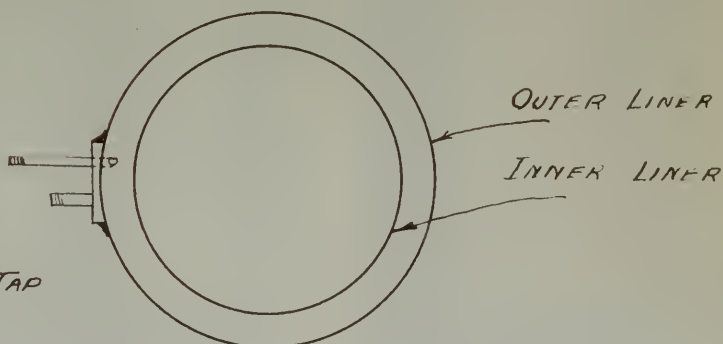


STATION 1

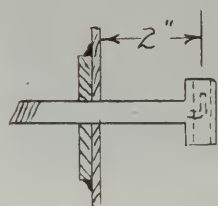
STATIC PRESSURE TAP



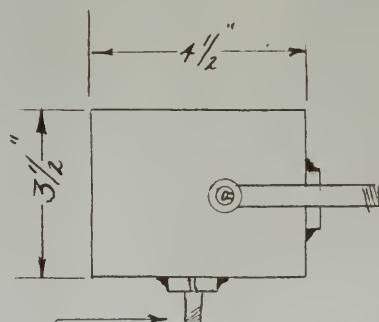
STATIC & TOTAL HEAD TAP



STATION 2, 3, 4.



TOTAL HEAD TUBE



STATION 5

STATIC PRESSURE TAP

C. A. THERMOCOUPLE RAKE

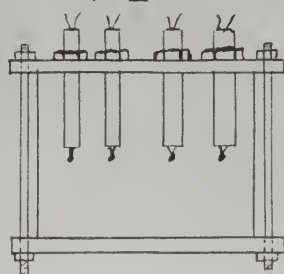


FIGURE 3

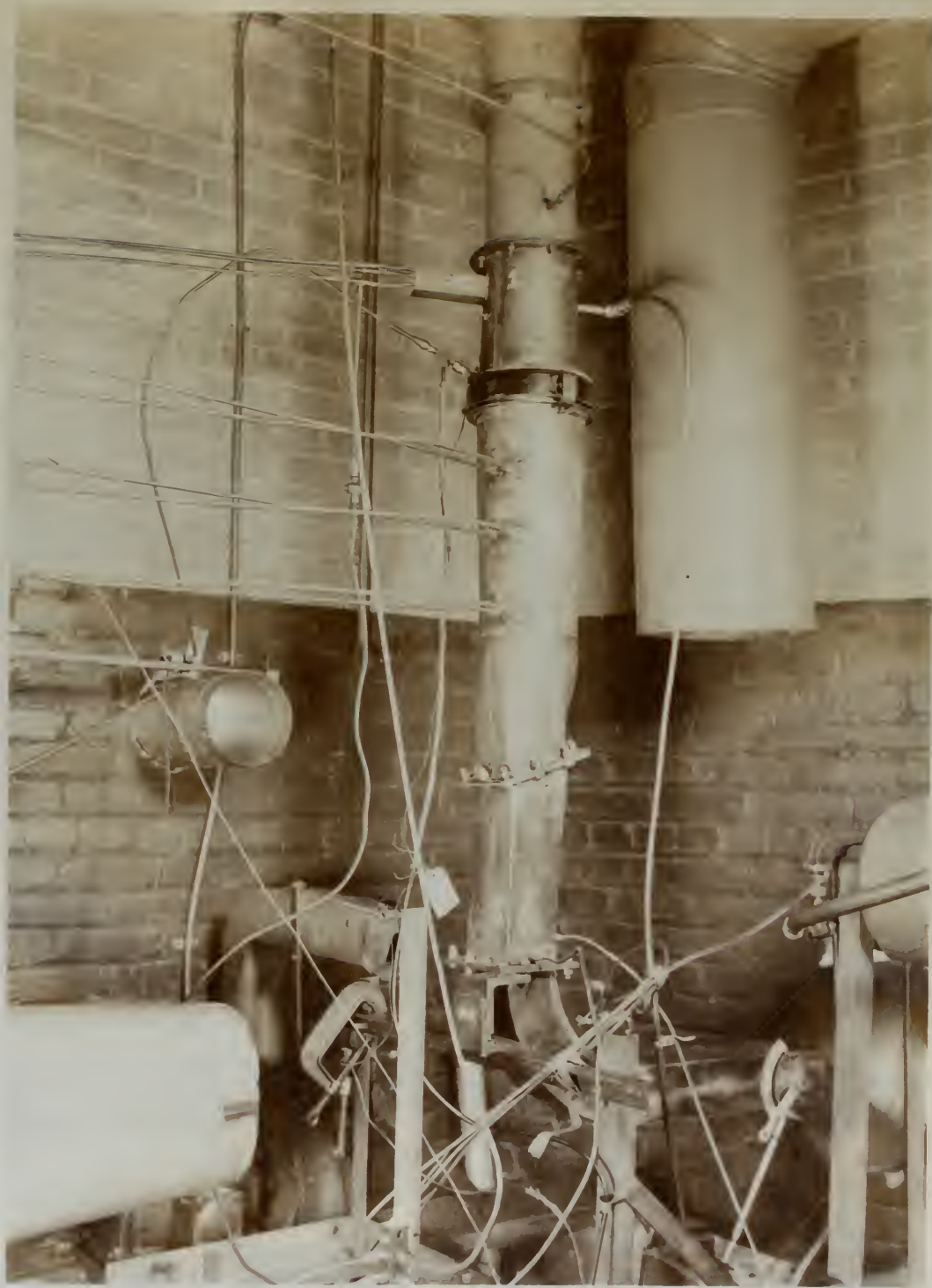


FIGURE 4

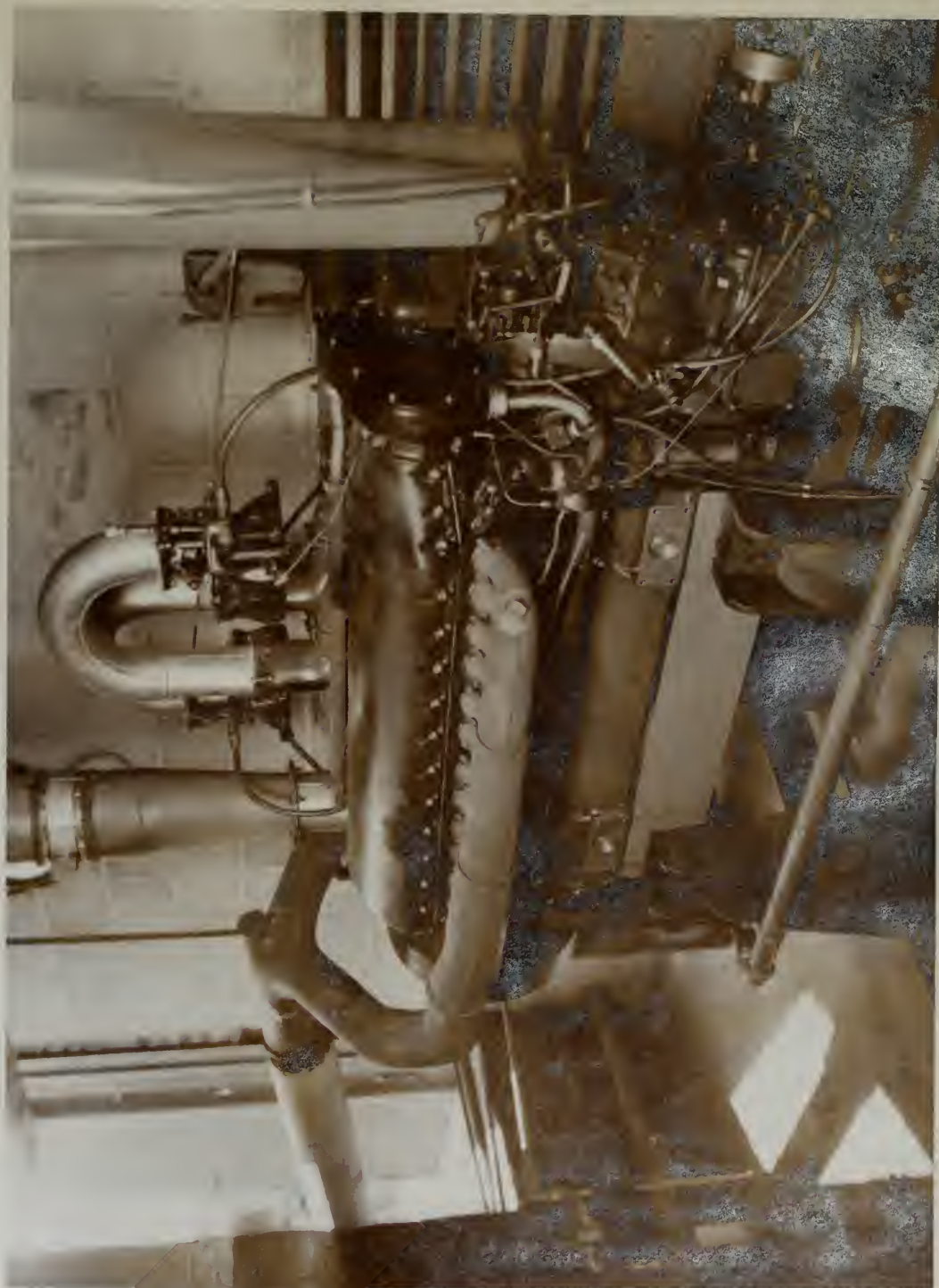


FIGURE 5

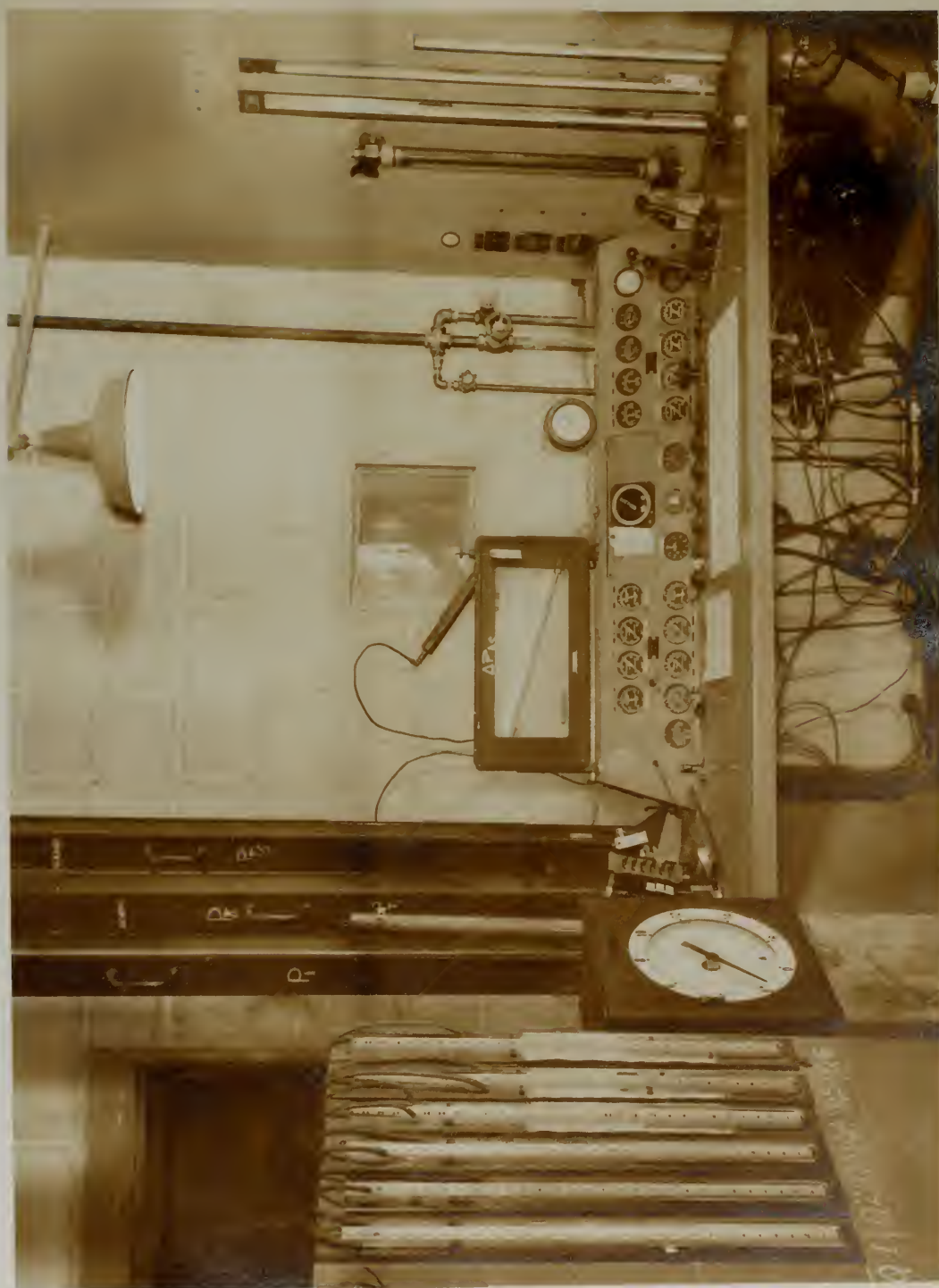


FIGURE 6

FIGURE 7

J-33 ENGINE DATA SCALED DOWN
FOR SINGLE BURNER OPERATION
ALLISON DIVISION
GENERAL MOTORS CORP.

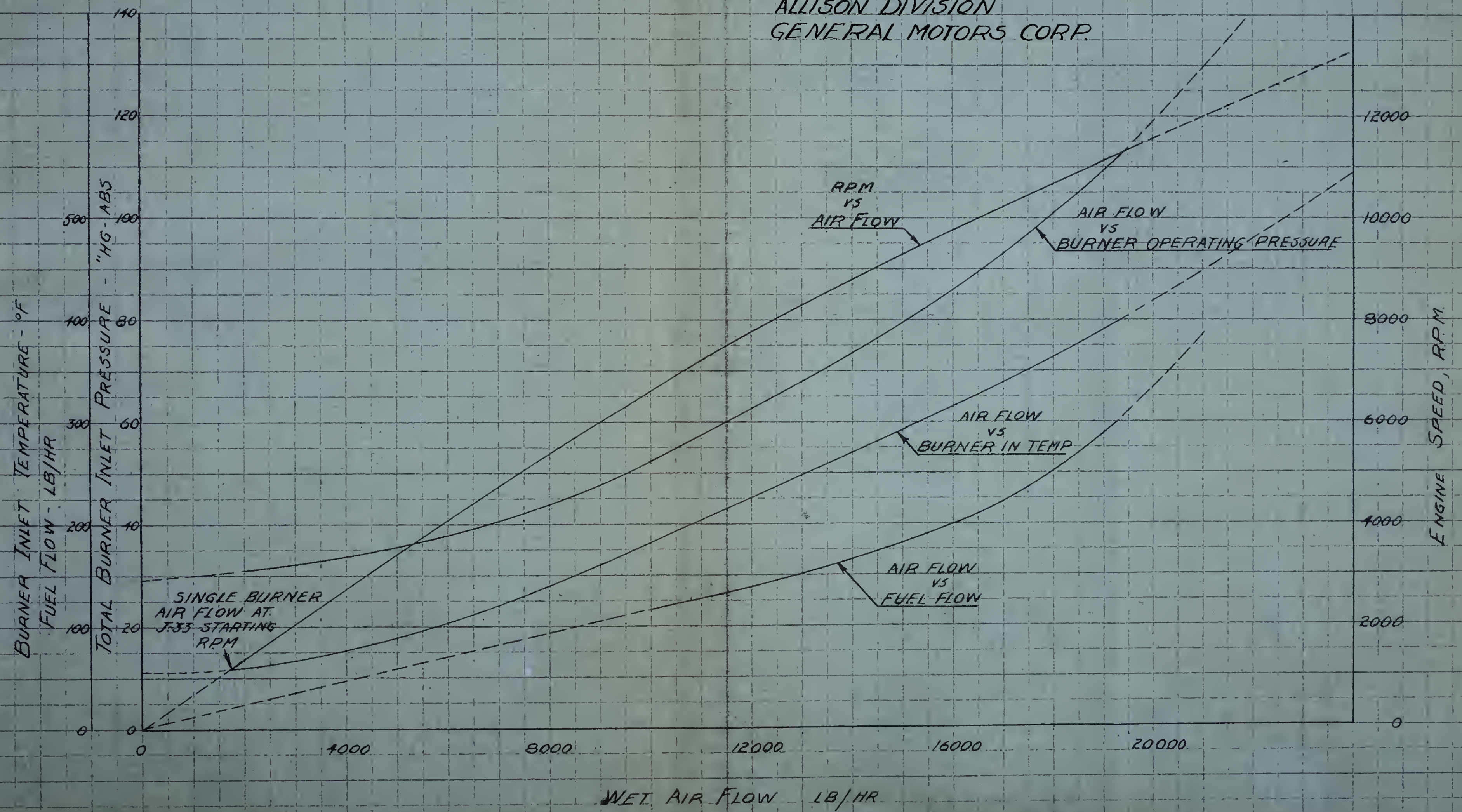
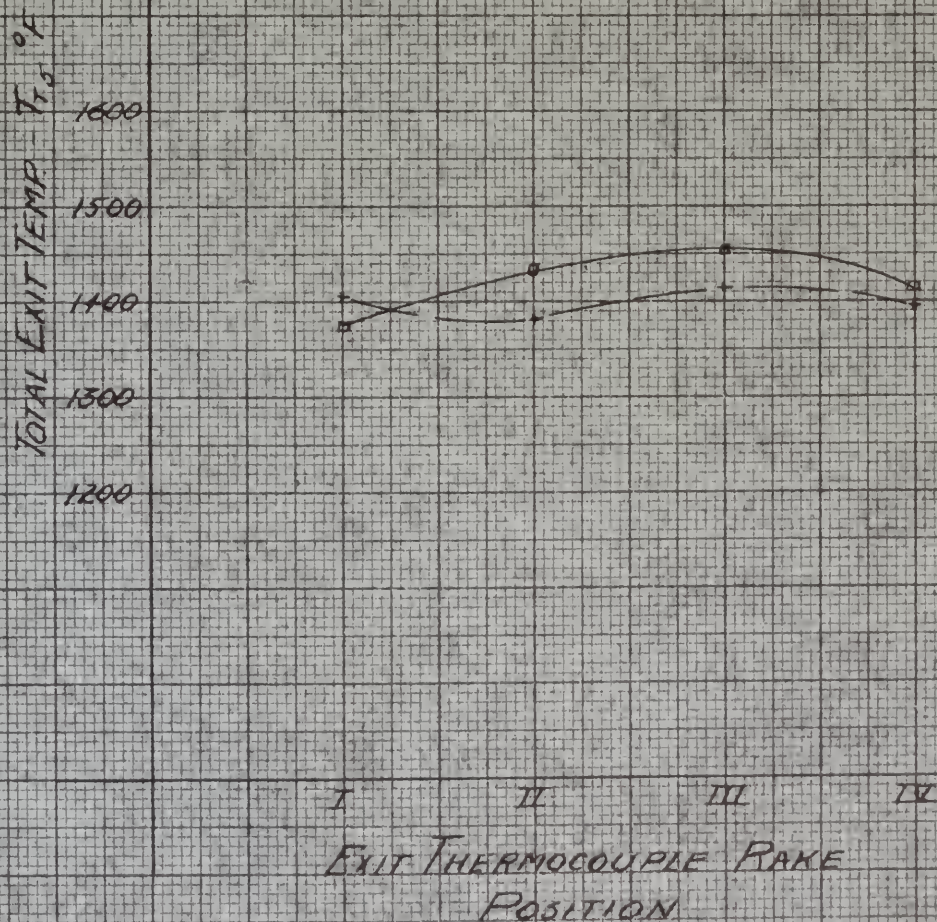
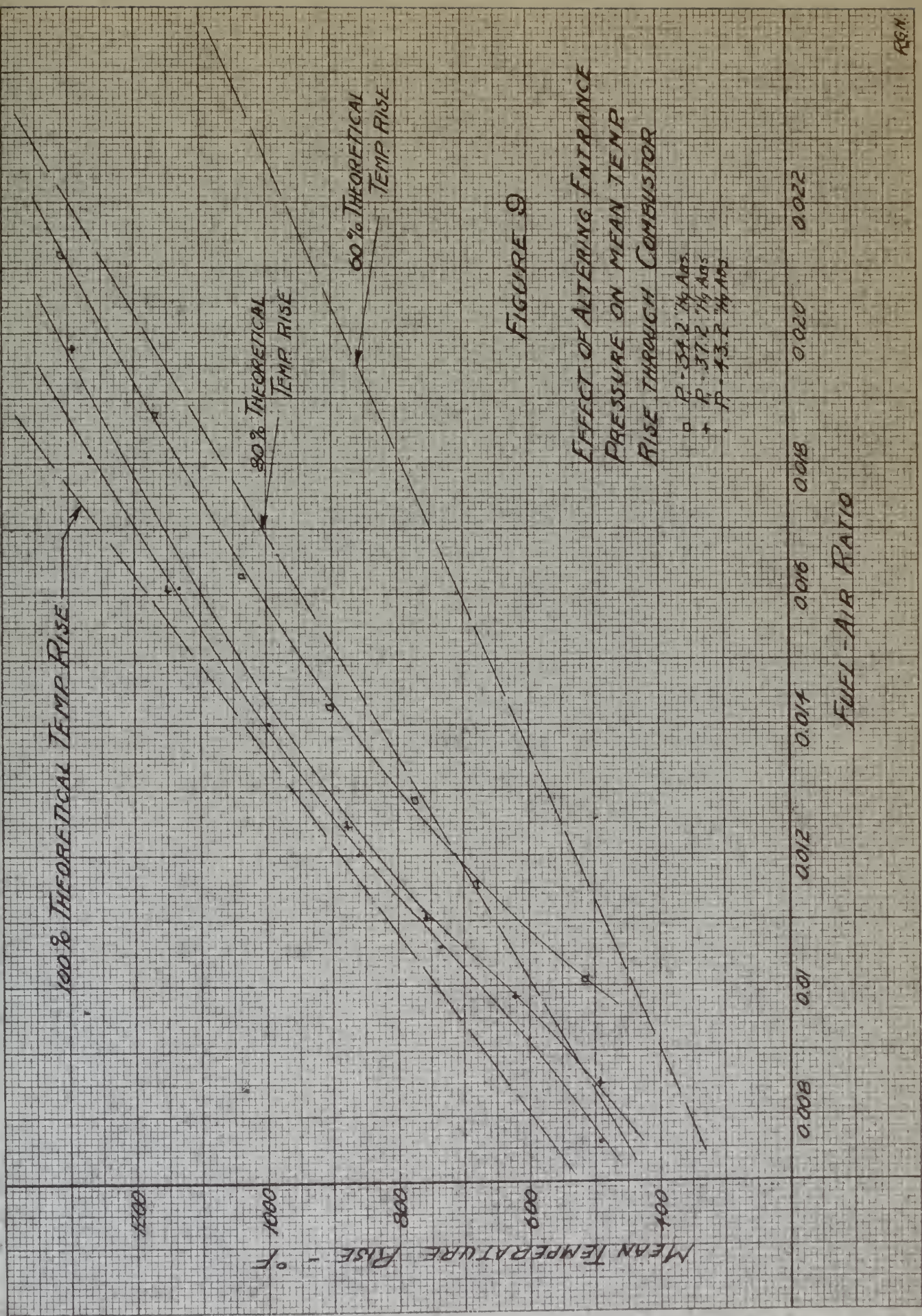


FIGURE 8

REPRESENTATIVE TEMPERATURE
DISTRIBUTION ACROSS EXIT
OF COMBUSTOR



REM

FIGURE 10

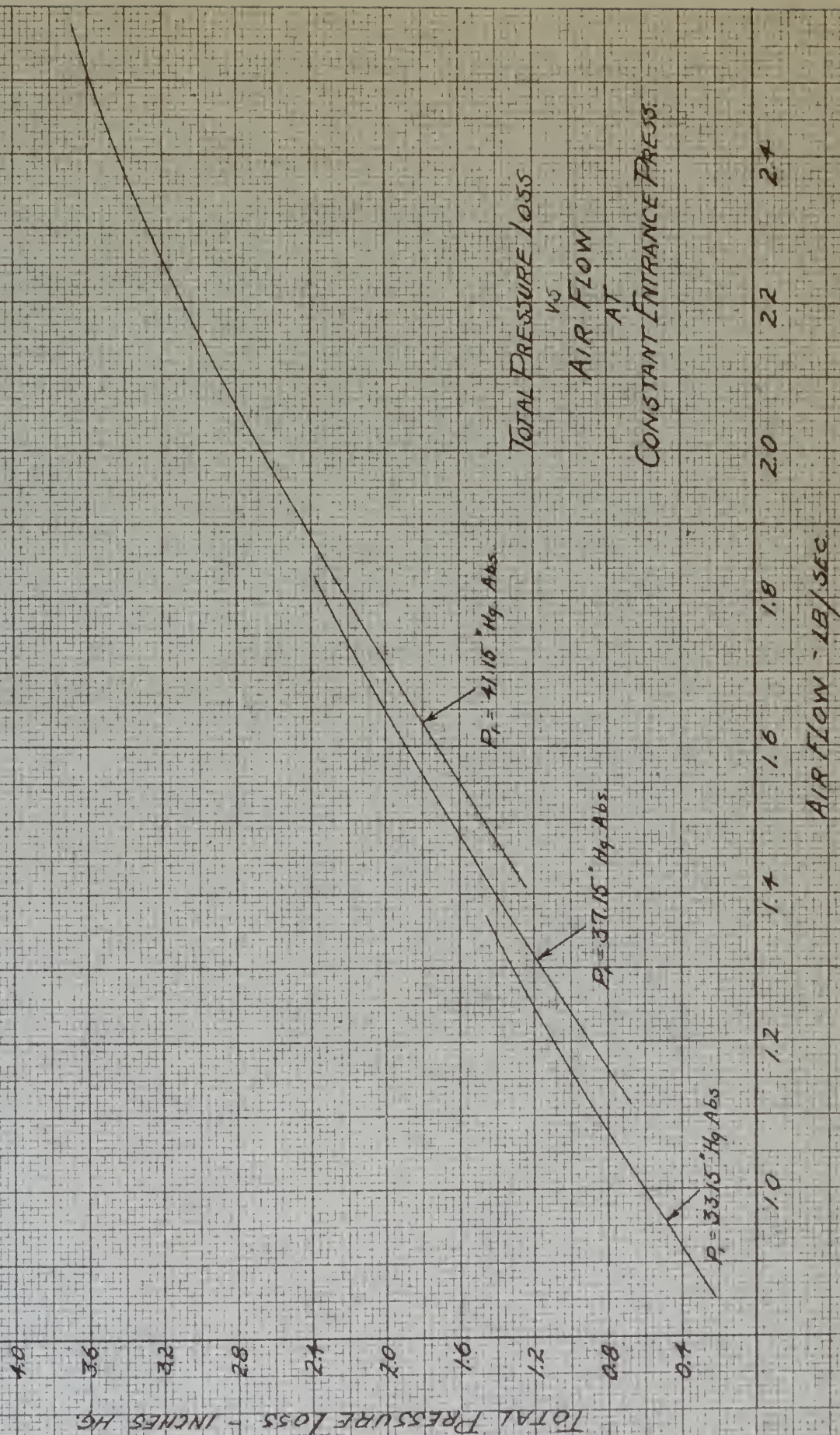


FIGURE 11

TOTAL PRESSURE LOSS
VS
AIR FLOW

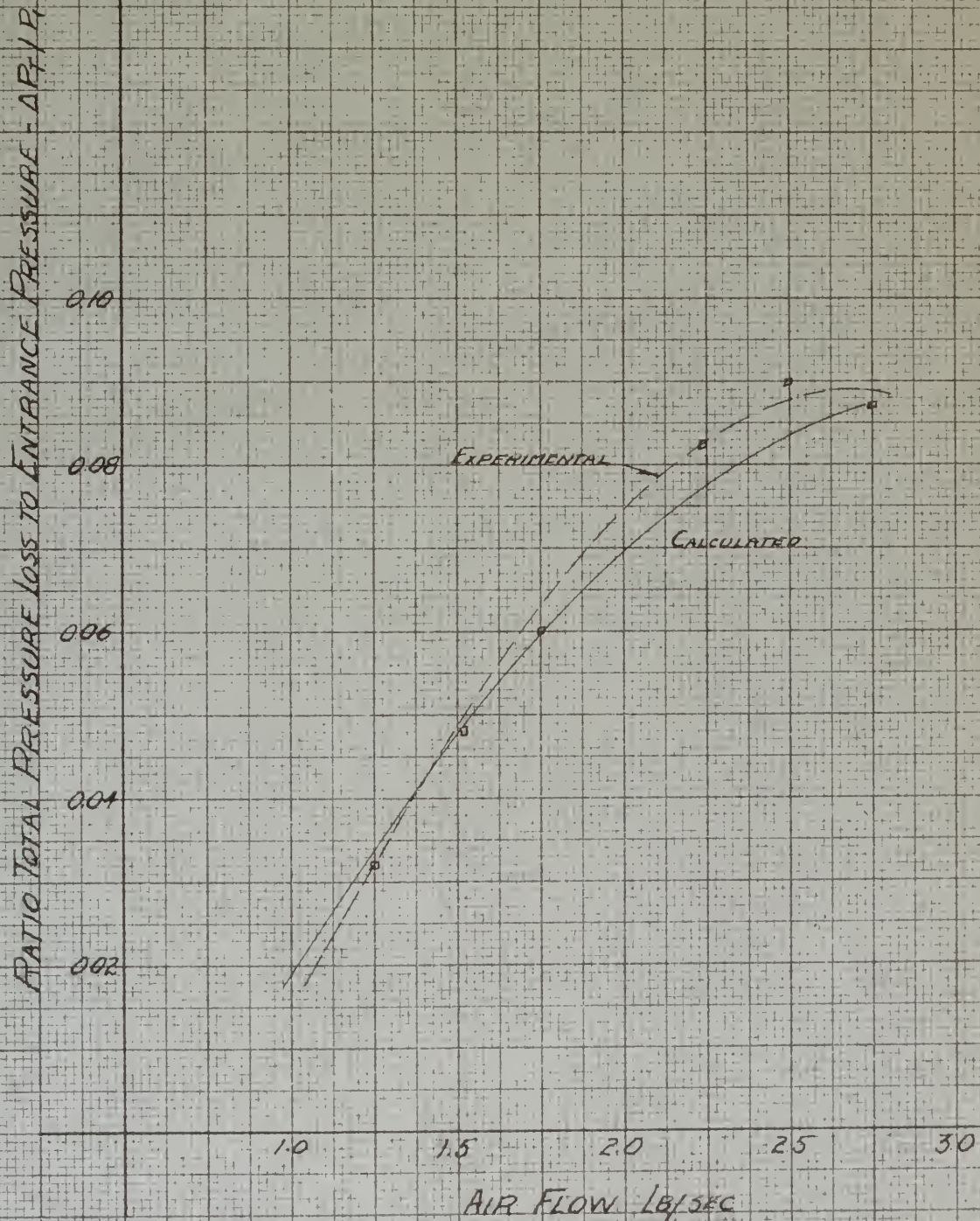


FIGURE 12

FRICTION PRESSURE LOSS

VS

AIR FLOW

- EXPERIMENTAL DATA
- CALCULATED - METHOD I
- CALCULATED - METHOD II

RATIO FRICTION PRESSURE LOSS TO ENTRANCE PRESSURE - $\Delta P_f / P_1$

0.10

0.08

0.06

0.04

0.02

EXPERIMENTAL

CALCULATED METHOD II

CALCULATED - METHOD I

1.0

1.5

2.0

2.5

3.0

AIR FLOW LB/SEC

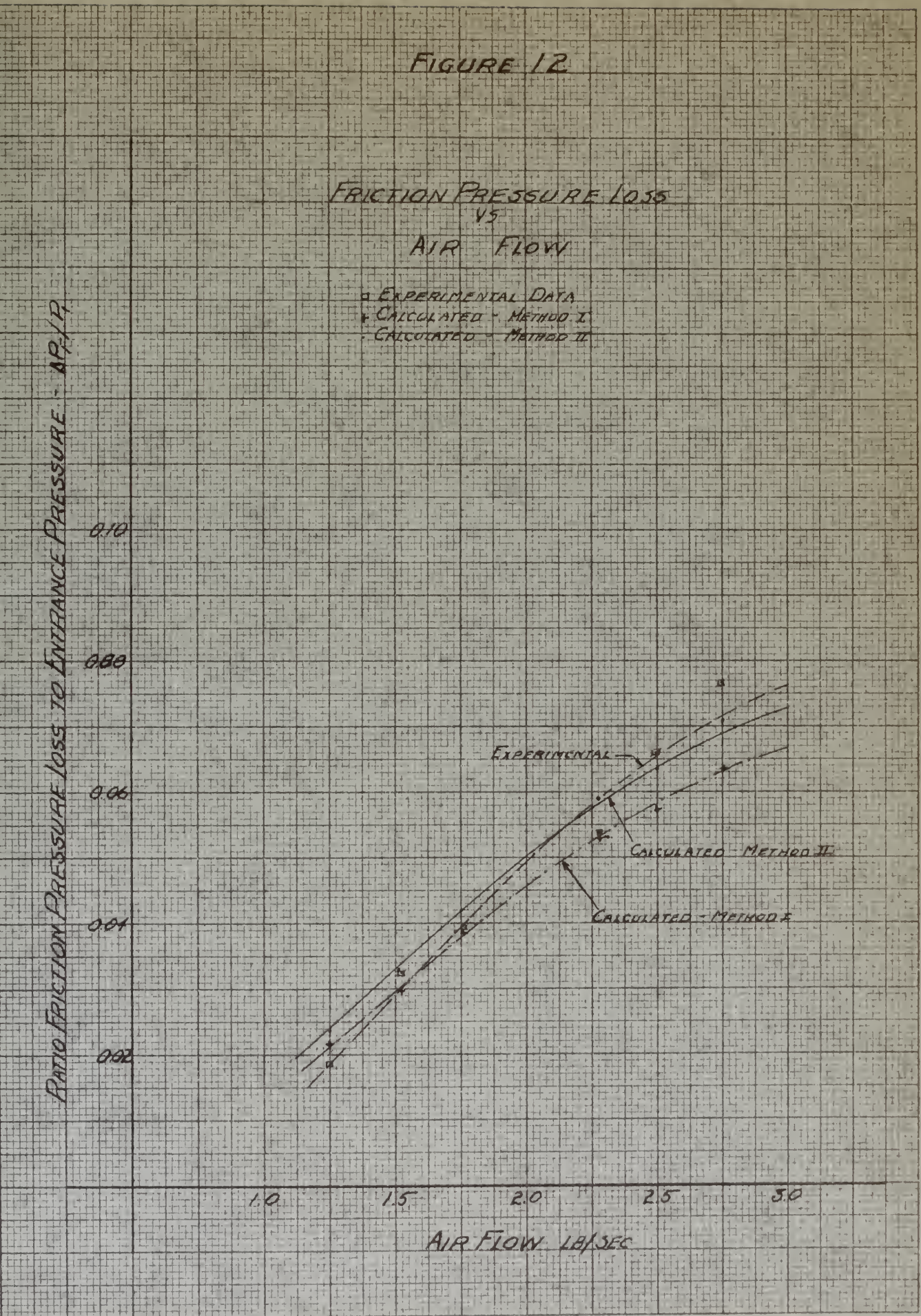


FIGURE 13

MOMENTUM PRESSURE LOSS
VS.
AIR FLOW

RATIO MOMENTUM PRESSURE LOSS TO ENTRANCE PRESSURE - $\Delta P_1 / P_1$

0.08

0.06

0.04

0.02

1.0

1.5

2.0

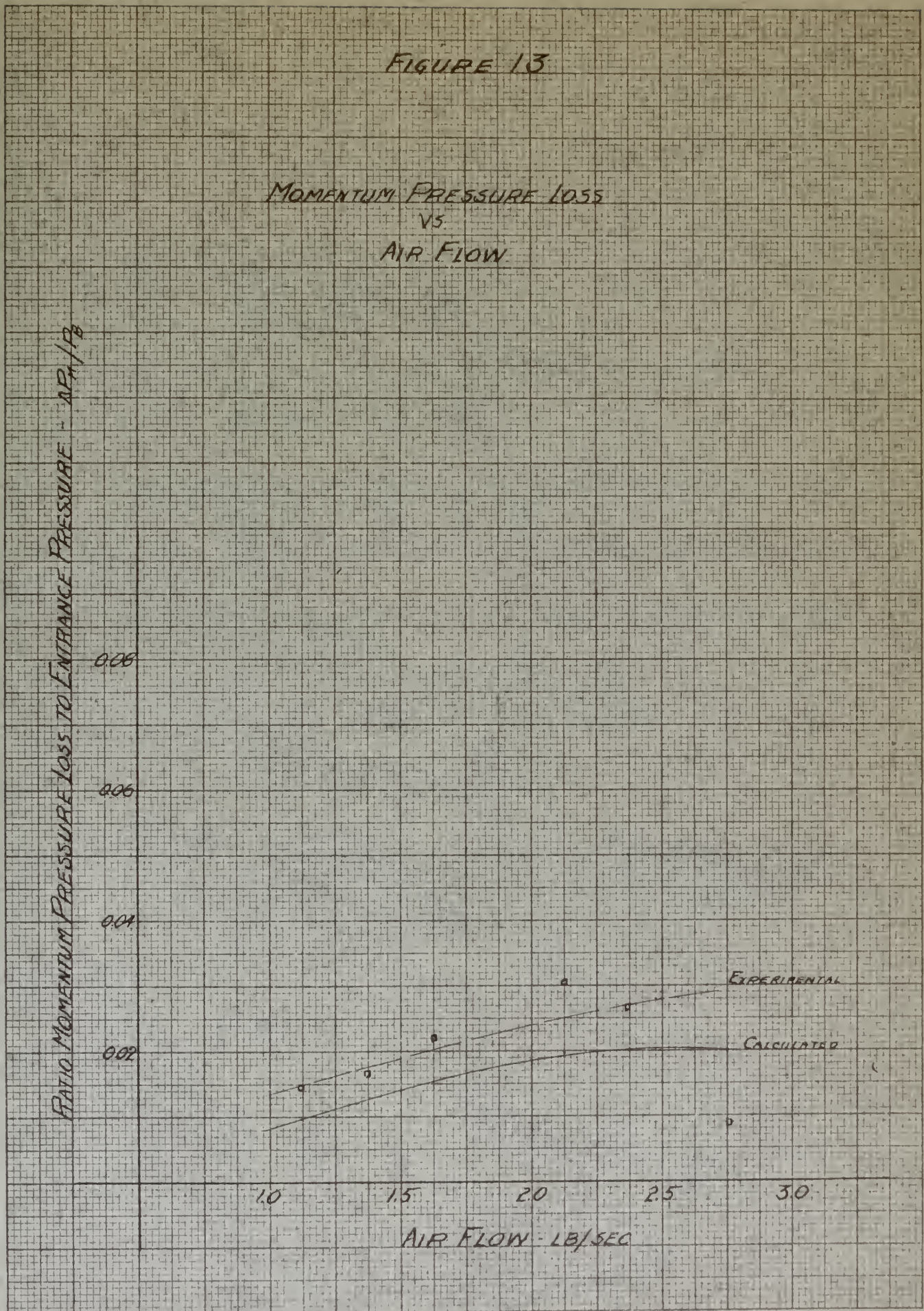
2.5

3.0

AIR FLOW - LB/SEC

EXPERIMENTAL

CALCULATED



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APPENDIX

CHAPTER I

THE first part of the book is devoted to a general survey of the subject, and to a discussion of the various methods which have been employed for its treatment.

The second part is devoted to a detailed examination of the various methods which have been employed for the treatment of the subject, and to a discussion of the results which have been obtained.

The third part is devoted to a detailed examination of the various methods which have been employed for the treatment of the subject, and to a discussion of the results which have been obtained.

CHAPTER II

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APPENDIX - ANALYSIS OF MOMENTUM PRESSURE DROP THROUGH COMBUSTOR

$$P_{T_1}/P_1 = (T_{T_1}/T_1)^{\gamma/\gamma-1}$$

$$P_{T_5}/P_5 = (T_{T_5}/T_5)^{\gamma/\gamma-1}$$

$$P_{T_5}/P_{T_1} = P_5/P_1 (T_{T_5}/T_{T_1})^{\gamma/\gamma-1} (T_1/T_5)^{\gamma/\gamma-1}$$

$$P = \rho R T$$

$$R T = P Q / \dot{W}$$

$$P_1 Q_1 / T_1 = R \dot{W} = P_5 Q_5 / T_5$$

$$P_1 V_1 / T_1 = P_5 V_5 / T_5$$

$$\begin{aligned} P_{T_5}/P_{T_1} &= V_1/V_5 \cdot T_5/T_1 (T_{T_5}/T_{T_1})^{\gamma/\gamma-1} (T_1/T_5)^{\gamma/\gamma-1} \\ &= V_1/V_5 (T_{T_5}/T_{T_1})^{\gamma/\gamma-1} (T_1/T_5)^{\gamma/\gamma-1} \end{aligned}$$

$$P_{T_5} = P_{T_1} V_1/V_5 (T_{T_5}/T_{T_1})^{\gamma/\gamma-1} / (T_5/T_1)^{\gamma/\gamma-1}$$

TO FIND T_1 & T_2

$$T_{T_1} = T_1 (1 + \frac{\gamma-1}{2} M_1^2)$$

$$M_1^2 = V_1^2/a^2 = V_1^2/\gamma g R T_1$$

$$T_{T_1} = T_1 \left[1 + \frac{\gamma-1}{2} (V_1^2/\gamma g R T_1) \right]$$

$$= T_1 + \frac{\gamma-1}{2} V_1^2/\gamma g R$$

$$= T_1 + V_1^2/2 g R (\gamma/\gamma-1)$$

$$T_1 = T_{T_1} - V_1^2/2 g R (\gamma/\gamma-1)$$

$$T_5 = T_{T_5} - V_5^2/2 g R (\gamma/\gamma-1)$$

TO FIND V_5

$$P_A - P_B A = \omega/g (V_5 - V_1)$$

$$P_Q/V_1 - P_5 Q_5/V_5 = \omega/g (V_5 - V_1)$$

$$PQ = RT P \frac{\omega}{g} = RT \omega$$

$$RT_1 \omega/V_1 - PT_5 \omega/V_5 = \omega/g (V_5 - V_1)$$

$$T_1/V_1 - T_5/V_5 = (V_5 - V_1)/Rg$$

DIVIDING (2) & (3) by V_1 & V_5

$$T_1/V_1 = \bar{T}_{T1}/V_1 - V_1/2gR(\gamma/\gamma-1)$$

$$T_5/V_5 = \bar{T}_{T5}/V_5 - V_5/2gR(\gamma/\gamma-1)$$

$$T_1/V_1 - T_5/V_5 = \bar{T}_{T1}/V_1 - \bar{T}_{T5}/V_5 + (V_5 - V_1)/2gR(\gamma/\gamma-1)$$

$$\bar{T}_{T1}/V_1 - \bar{T}_{T5}/V_5 + (V_5 - V_1)/2gR(\gamma/\gamma-1) = 1/Rg (V_5 - V_1)$$

$$\bar{T}_{T1}/V_1 - \bar{T}_{T5}/V_5 = 1/Rg (V_5 - V_1) - (V_5 - V_1)/2gR(\gamma/\gamma-1)$$

$$= (V_5 - V_1) \left(\frac{1}{Rg} - \frac{1}{2gR(\gamma/\gamma-1)} \right)$$

$$= (V_5 - V_1) \left(\frac{2\gamma - (\gamma-1)}{2gR\gamma} \right)$$

$$= (V_5 - V_1) \left(\frac{\gamma+1}{2gR} \right)$$

$$\bar{T}_{T1}/V_1 \left[1 - \frac{\bar{T}_{T5}/V_5}{\bar{T}_{T1}/V_1} \right] = \left(\frac{\gamma+1}{2gR} \right) V_1 (V_5/V_1 - 1)$$

$$\bar{T}_{T1}/V_1 \left[1 - \frac{\bar{T}_{T5}}{\bar{T}_{T1}} \frac{V_1}{V_5} \right] = \dots$$

$$1 - \frac{\bar{T}_{T5}}{\bar{T}_{T1}} \frac{V_1}{V_5} = \frac{\gamma+1}{2} (M_{1T}^2) \left(\frac{V_5}{V_1} - 1 \right)$$

$$1 - \frac{\bar{T}_{T5}/\bar{T}_{T1}}{V_5/V_1} = \frac{\gamma+1}{2} (M_{1T}^2) \frac{V_5}{V_1} - \frac{\gamma+1}{2} M_{1T}^2$$

$$1 + \frac{\gamma+1}{2} M_{1T}^2 = \frac{\gamma+1}{2} M_{1T}^2 \frac{V_5}{V_1} + \frac{\bar{T}_{T5}}{\bar{T}_{T1}} \frac{V_5}{V_1}$$

$$\left(V_5/V_1 \right)^2 \frac{\gamma+1}{2} M_{1T}^2 - V_5/V_1 \left[1 + \frac{\gamma+1}{2} M_{1T}^2 \right] + \bar{T}_{T5}/\bar{T}_{T1} = 0$$

$$V_5/V_1 = 1 + \frac{\gamma+1}{2} M_{1T}^2 \pm \sqrt{\left(1 + \frac{\gamma+1}{2} M_{1T}^2 \right)^2 - 4 \left(\frac{\gamma+1}{2} M_{1T}^2 \right) \bar{T}_{T5}/\bar{T}_{T1}} / \left(\frac{\gamma+1}{2} M_{1T}^2 \right)$$

ANALYSIS OF FRICTION PRESSURE DROP THROUGH THE COMBUSTION CHAMBER

FLOW THROUGH AN ORIFICE

$$\Delta P_F = \rho/29 \left[\frac{Q}{P} \frac{\sqrt{1 - \left(\frac{A_1}{A_2}\right)^4}}{A_2 C} \right]^2$$

A_1 = AREA IN ANNULAR SPACE, SQUARE FEET

A_2 = ORIFICE AREA, SQUARE FEET

C = ORIFICE COEFFICIENT

ΔP = PRESSURE DROP ACROSS ORIFICE, LB/SQ.FT.

ρ = DENSITY OF FLUID, LB/FT³

Q = MASS FLOW THROUGH ORIFICE, CU.FT./SEC

ASSUME PARALLEL FLOW SYSTEM. PRESSURE DROP ACROSS ONE ORIFICE EQUALS PRESSURE DROP ACROSS ANY ORIFICE. CHECK FOR CONSTANT MASS FLOW.

SYMBOLS

The symbols used in this paper are those being currently used for turbo-jet engines.

A	Area of any cross section, square feet
M	Mach number, ratio of airspeed to local speed of sound
P_T	Total pressure, pounds per square foot or inches of mercury
P	Static pressure, pounds per square foot or inches of mercury
ΔP_T	Total pressure loss due to friction and heat addition, inches of mercury
ΔP_F	Friction pressure loss, inches of mercury
ΔP_M	Momentum pressure loss, inches of mercury
T_T	Total temperature, degrees Rankine
T	Static temperature, degrees Rankine
V	Velocity of gas flow, feet per second
\dot{W}	Air mass flow, pounds per second
\dot{Q}	Air mass flow, cubic feet per second
γ	Ratio of specific heat at constant pressure to specific heat at constant volume
ρ	Density of air, pounds per cubic foot

Subscripts

1	Combustor inlet
5	Combustor outlet
E	Equivalent combustor or constant cross-sectional area

ANNEX

The following table is a summary of the results of the

survey conducted in the year 1960.

1. The total number of respondents was 1000.

2. The results of the survey are as follows:

3. The following table shows the results of the survey:

4. The results of the survey are as follows:

5. The following table shows the results of the survey:

6. The results of the survey are as follows:

7. The following table shows the results of the survey:

8. The results of the survey are as follows:

9. The following table shows the results of the survey:

10. The results of the survey are as follows:

11. The following table shows the results of the survey:

12. The results of the survey are as follows:

13. The following table shows the results of the survey:

14. The results of the survey are as follows:

15. The following table shows the results of the survey:

16. The results of the survey are as follows:

17. The following table shows the results of the survey:

18. The results of the survey are as follows:

19. The following table shows the results of the survey:

20. The results of the survey are as follows:

21. The following table shows the results of the survey:

22. The results of the survey are as follows:

Line	Description	Amount	Total
1	Balance forward	100.00	100.00
2	Interest on loan	5.00	105.00
3	Principal payment	10.00	95.00
4	Interest on loan	5.00	100.00
5	Principal payment	10.00	90.00
6	Interest on loan	5.00	85.00
7	Principal payment	10.00	75.00
8	Interest on loan	5.00	70.00
9	Principal payment	10.00	60.00
10	Interest on loan	5.00	55.00
11	Principal payment	10.00	45.00
12	Interest on loan	5.00	40.00
13	Principal payment	10.00	30.00
14	Interest on loan	5.00	25.00
15	Principal payment	10.00	15.00
16	Interest on loan	5.00	10.00
17	Principal payment	10.00	0.00

DATE DUE

21 FE'50

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N42 Nester

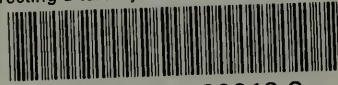
Testing a turbo-jet
combustion chamber to
check analytical design.

Thesis 11471
N42 Nester

Testing a turbo-jet
combustion chamber to
check analytical design.

thesN42

Testing a turbo-jet combustion chamber t



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